A Shock Dynamic Study of High-Speed Impact onto Condensed Matter

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論 文 内 容 要 旨

Fluid motions are divided into the steady flow, which is independent from time, and the unsteady flow, which varies with the elapse of time. The flow in a wind tunnel is considered as the steady flow approximately. Strictly speaking, however, the steady flow totally independent from time is unreal and is just idealized flow. To consider flow as varying with time, such as a turbulent flow, is more universal. In terms of flow velocities, low speed flow, which is much slower than the speed of sound, is defined as the incompressible flow. In incompressible flow, the density of a fluid unvaried so that the speed of sound of the fluid is considered to be infinity. In contrast, when fluid motion is comparable to the local speed of sound, it exhibits compressibility. According to whether flow speed is lower or higher than the speed of sound, it is called subsonic and supersonic flow, respectively. The propagation of a shock wave is a typical compressible unsteady flow.

In a shock wave experiment, advanced measurement instrument with extreme high temporal resolution is necessary to capture thin discontinuous wave front moving at high speed. High-speed video cameras which were able to capture the propagation of a shock wave were developed by improvement of semiconductor sensors. The image processing technology was developed well and the pressure measuring devices was also improved as well. It should be emphasized that the progress of supercomputers has enabled to accurately solve hyperbolic partial differential equations, which described the compressible fluid motion, and to readily reproduce experimental results. Hence, we can now investigate shock wave phenomena occurring on gas/liquid interface, which had been considered as impossible to quantitatively study.

A ballistic range which can launch a projectile at high speeds is one of experimental facilities in fluids science, while flow field around a model installed in the test section is measured in a wind tunnel. Various ballistic ranges, for example a two-stage light gas gun, a powder gun and a rail gun, were suggested. A ballistic range has a merit of choosing not only wide range of Mach numbers but also Reynolds numbers and has limitations of the size of projectiles and the precise measurement of their flow fields. Moreover, a ballistic range has a unique property that it can produce transonic flows near Mach number one which cannot be obtained in the wind tunnel.

Measurement of the shock standoff distance over a sphere at hypersonic or supersonic velocity ranges is one of benchmark tests in experimental study of high-speed gasdynamics. The shock standoff distance at hypersonic range becomes larger than the shock standoff distance on an assumption of the constant ratio of specific heats. It is called the real gas effect that the ratio of specific heats varies with both Mach number and the pressure of the uniform flow. The shock standoff distance at hypersonic range represents the real gas effect behind the shock wave. The shock standoff distance over a sphere at transonic range, especially at nearsonic which means near Mach number one, was reported experimentally and analytically. Reported analytical models agreed with experiment at supersonic range. The shock standoff distance asymptotically decreases as Mach number increases. In analysis, a detached shock wave at Mach number one appears at infinity. In numerical simulation, the shock standoff distance at Mach number one cannot converge. In experiment performed in ballistic ranges, however, the shock standoff distance at nearsonic range is smaller than the analytical solution. Hence, the shock standoff distance at transonic range can be considered to represent the unsteady effect. This motivates the detailed ballistic range experiment at the transonic range. The water entry of a sphere is a complex flow phenomenon consisting of both gas and liquid phases accompanied with huge deformation of gas/liquid interface. An underwater shock wave driven by the high-speed water entry of the projectile is not only a research issue of the elementary physics but also interdisciplinary researches related with a meteoroid impact into the ocean, such as a mass extinction at Cretaceous / Tertiary boundary in geology field and the Amino acid synthesis contributing a life manifestation in life science field. Generally, the impact velocity of a meteoroid exceeds 10 km/s. Although the numerical simulation can calculate in this velocity range, existing numerical data were not compared with the experiment. To verify the results of numerical simulations, the comparison with experimental results is indispensable. Hence, to obtain experimental data about high-speed water entry and to discuss the velocity dependence of phenomena are essential issues. In this thesis, the relation between the entry speed and various phenomena following with the high-speed entry into water are experimentally investigated.

Chapter 1 is the introduction describing the research backgrounds.

In Chapter 2, ballistic range experiment techniques are developed. Ballistic ranges used in experiments were introduced in detail. The piston of diaphragm-less system of the single stage gas gun mode in the horizontal ballistic range which can launch at velocity ranging from 200 m/s to 500 m/s was optimized empirically. In this system, the moving backward of a piston which seals the high-pressure room filled with the driver gas means the rupture of a virtual diaphragm between the high-pressure room and the launch tube, and is called the quick-opening valve. The ability of the quick-opening valve of the diaphragm-less system was improved by reduction of the piston weight and the mechanical friction drag as much as possible. The improved gas gun was confirmed to launch a large diameter sphere with controlling muzzle velocity accurately. The operation mode of the oblique ballistic range was extended for extending the range of muzzle velocity which was enough to the water entry experimental condition. When a smaller or a complex shaped projectile such as a sphere and a slender body is launched, the projectile is installed in a sabot which is a cylindrical support of same diameter as the launch tube and the sabot including the projectile is launched. The sabot separates from the projectile by using aerodynamic drag in the recovery tank. Some distance is necessary for this separation and is called the sabot separation distance. Development of the enforced sabot separation technique using driver gas pressure behind the sabot shortened the sabot separation distance. The machining accuracy of a sabot caused scatter of the projectile trajectory. This scatter was able to be fixed by adding a spot facing.

In Chapter 3, the shock standoff distance over a decelerating free-flight sphere at transonic range launched by the single-stage gas gun mode in the horizontal ballistic range was measured and is discussed. It seems the flow field around a decelerating free-flight sphere is similar to the flow field in water entry on the point that flow field includes both a sphere decelerating from supersonic range and a detached shock wave. A 40 mm diameter polycarbonate sphere and a 7.9 mm aluminum sphere were used of the experiment. A detached shock wave and a sphere were visualized by shadow graph and sequential photographs were recorded in a high-speed video camera. In comparison with past experiments in ballistic range and analytical models assumed the steady flow, they were completely different at nearsoinc range. A detached shock wave was observed in front of the sphere with the finite standoff distance even if the sphere velocity was lower than 0.90 in Mach number. The idea of the steady flow was not be able to be applied to this flow field. A interferogram image of flow field around a 40 mm diameter polycarbonate sphere was visualized by the double exposure holographic interferometer. The development of the boundary layer along a sphere surface, the structure of the expansion wave behind the sphere and the structure of the wake flow were displayed as stripes distribution. It is possible to calculate density distribution on an assumption of axisymmetric flow. These data should be compared with the numerical simulation of the unsteady flow in future.

In Chapter 4, shock wave and gas/liquid interface phenomena following with a high-speed water entry are discussed. A 5 mm diameter stainless steel sphere installed in a polycarbonate sabot was accelerated and launched by the oblique ballistic range. The time evolution of various phenomena following with the water entry were visualized by both shadow graph and direct photography with diffused light. The pressure of the underwater shock wave driven by the entry was measured at some depth by piezoelectric pressure transducers. The entry of a high-speed sphere into water caused a water splash and a shock wave in air and caused a cavity and an underwater shock wave in water. The relation between the vertical location of tip of the splash was linear to the vertical velocity of the splash. The resulting approximation of the motion of splash agreed well with experiments except for the condition at low entry speed. The initial velocity of the splash was lower than the entry speed. The ratio of velocities which were the initial velocity of the splash and the entry speed was independent from the entry speed and was constant. The propagation in horizontal direction of a shock wave in air driven by the entry agreed well with a similar law of the propagation of a spherical shock wave driven by a micro explosion of charge. In this scaling, the kinetic energy of the entry sphere was used instead of the energy of charge. The motion of an underwater projectile after the entry into water was dominated by the usual theory of a flight body. The projectile suffers impact load in extreme short time and decelerates rapidly. Then the projectile travels suffering by drag force in water when the projectile enters into water. The ratio of velocities which were the velocity just after rapid deceleration and the entry speed was independent from the entry speed and was constant. The drag coefficient of the sphere was able to be considered as constant in all velocity range and its value was 0.3332. The overpressure of an underwater shock wave increased proportional to the entry speed. The analogy between an underwater shock wave driven by the entry and an underwater shock wave driven by an underwater micro explosion was not confirmed. From analysis about the motion of cavity wall, the time at each depth when cavity diameter became maximum had positive correlation with the entry speed.

In Chapter 5, the conclusions of the present study are given.

論文審査結果の要旨

球の水中への突入は，気液界面の大変形を伴う，気相･液相が混在する複雑系の流れである。また，高速水中突入にともなう水中衝撃波現象は，工学的素過程の研究であるばかりでなく，海洋への隕石衝突に誘起される諸現象に結びつく。白亜紀/第三紀(K-T)の生物大量絶滅は，小惑星衝突に起因するとされており，ユカタン半島の沖に巨大な衝突孔が発見されて，放射性同位体計測がこれを実証している。海洋に衝突する隕石の速度は10 km/s を超え，強い水中衝撃波を発生したと考えられている。また，原始海洋でのアミノ酸の合成など，生命発生に貢献する物質合成には水中衝撃波の存在が関わったと考えられている。これらの数値シミュレーションは行われてきたが，これまで実験研究はなかった。数値計算結果の検証には，実験との対比が不可欠であり，高速の水中突入実験でのデータ取得，現象の速度依存性の検証は必須の研究課題である。そこで，本研究では，凝縮媒体への衝突現象を衝撃波工学的に解明することを目的として，弾道飛行装置を用いた実験研究を行っている。本論文は，これらの研究成果をまとめたものであり，全編5章からなる。

第1章は序論であり，本研究の背景，目的を述べている。

第2章では，本研究を実施するために必要な弾道飛行装置の開発を行っている。一段式軽ガス銃の無隔膜機構を改良し，大口径の飛行体の高精度撃ち出しを実現している。また，垂直打ち出し装置の運転形式を拡張し，目標速度範囲を達成している。さらに，駆動気体圧力を利用したサボ分離機構を提案し，サボ分離距離の短縮を実現している。これらの成果は本研究が目的を達成するために，有効かつ重要な成果である。

第3章では，開発した軽ガス銃を用いて射出した超音速から高亜音速で自由飛行する球が作る流れを議論している。球の速度が亜音速に遷移した後も，球の前方には離脱衝撃波が存在し，本質的に非定常な流れであることを確認している。また，二重露光ホログラフィ干渉計を用いて，球周りの流れを定量的に可視化している。これらの結果は，弾道飛行装置を用いることによって初めて得られるもので，これまでにない有益な成果である。

第4章では，縦型弾道飛行装置を用いて，球の水中突入現象について，200～1600 m/s の広い速度領域で突入速度の影響を議論している。水中突入に伴う諸現象を高速度直接撮影と影写真可視化計測し，王冠液滴の初速度と突入速度の比は一定であり，液滴が駆動した気中の衝撃波の水平伝播には，突入物体の運動エネルギによるスケーリング則が成立することを確認している。また，水中突入前後の球の速度比が一定であり，突入直後の抗力係数は全速度領域で一定で $C_D = 0.3332$ となり，水中衝撃波の過剰圧は突入速度に対して線形に増加することを確認している。これらの結果は，従来の実験研究を大幅に超える高速の水中突入により新たな知見を得たもので，非常に重要な成果である。

第5章は結論であり，本論文を総括している。

以上要するに本論文は，弾道飛行装置を用いて，球の飛行および水中突入現象を広い速度領域で計測し，非定常現象の速度依存性を解明したもので，航空宇宙工学及び衝撃波工学の発展に寄与するところが少なくない。

よって，本論文は博士(工学)の学位論文として合格と認める。